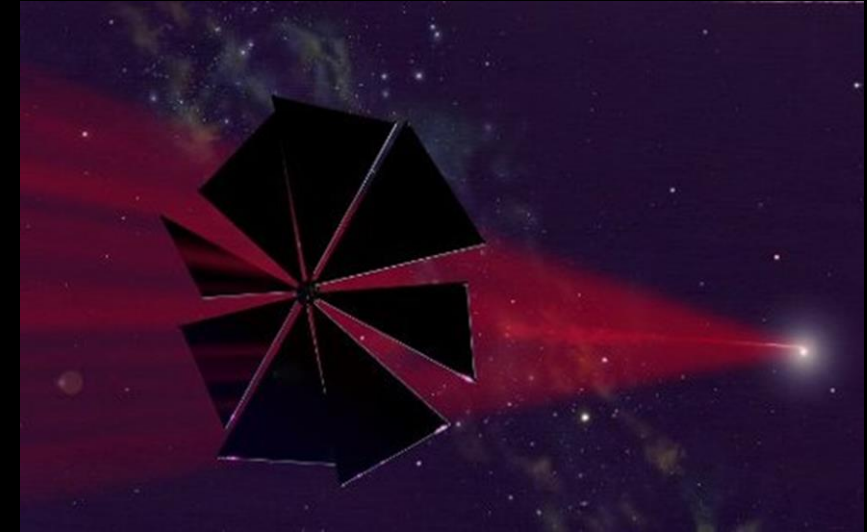
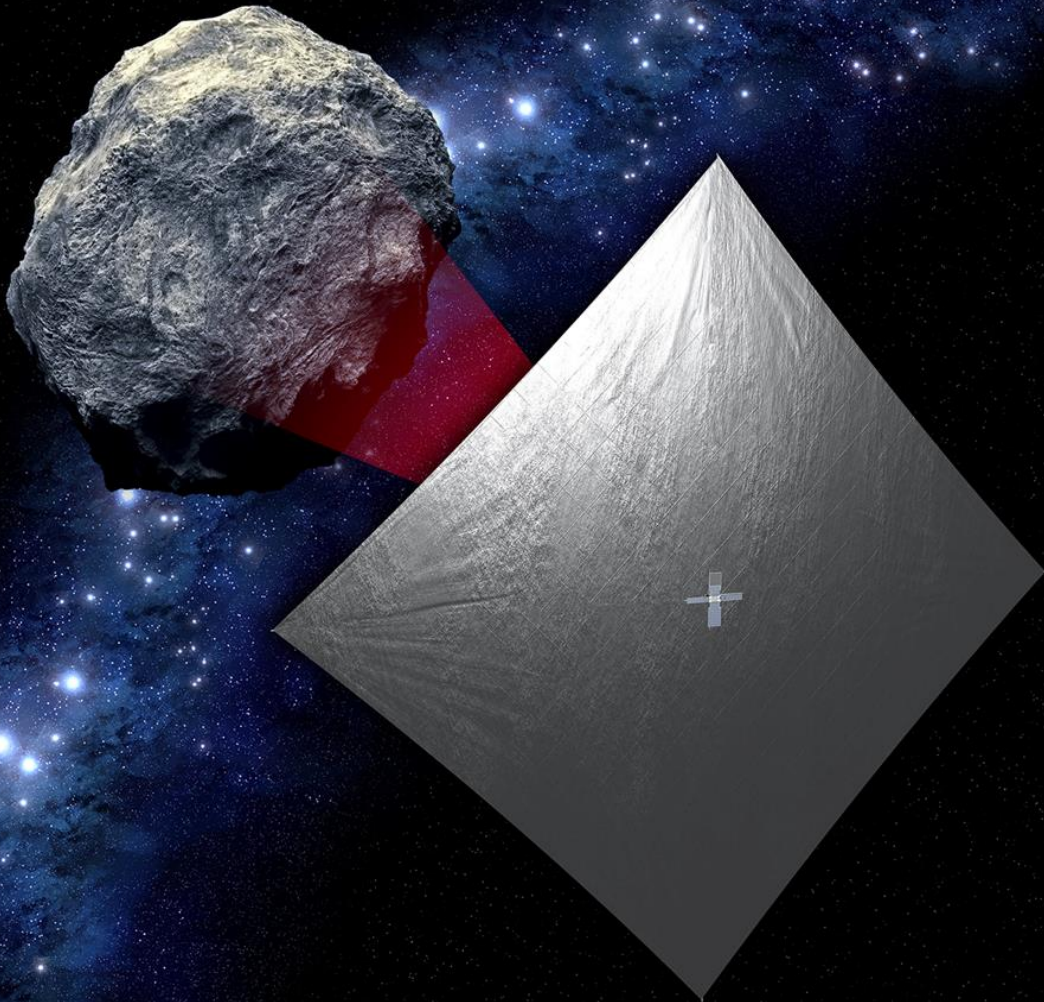




# Solar Sails



Les Johnson

George C. Marshall Space Flight Center



We tend to think of space as being

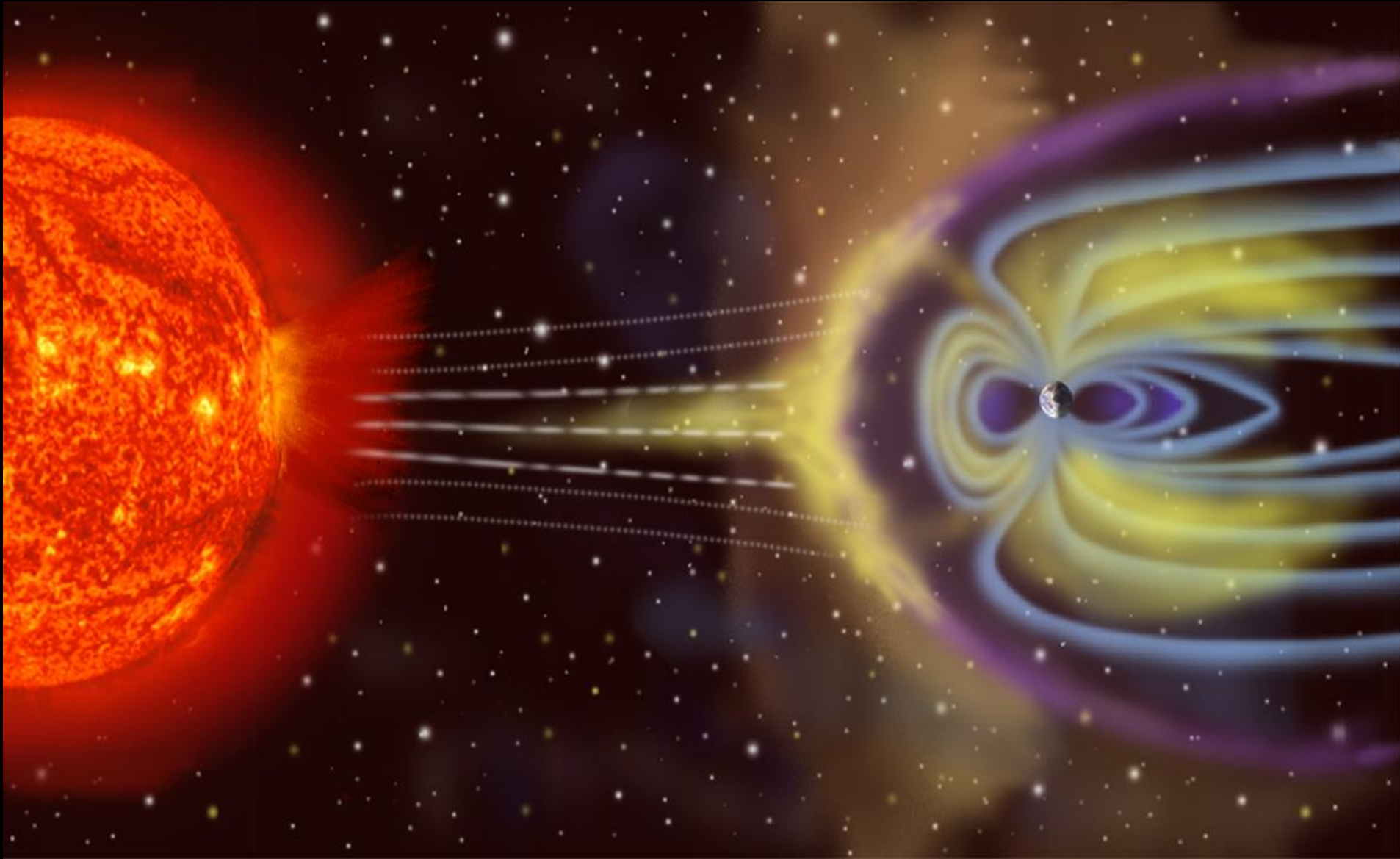
*big and empty...*







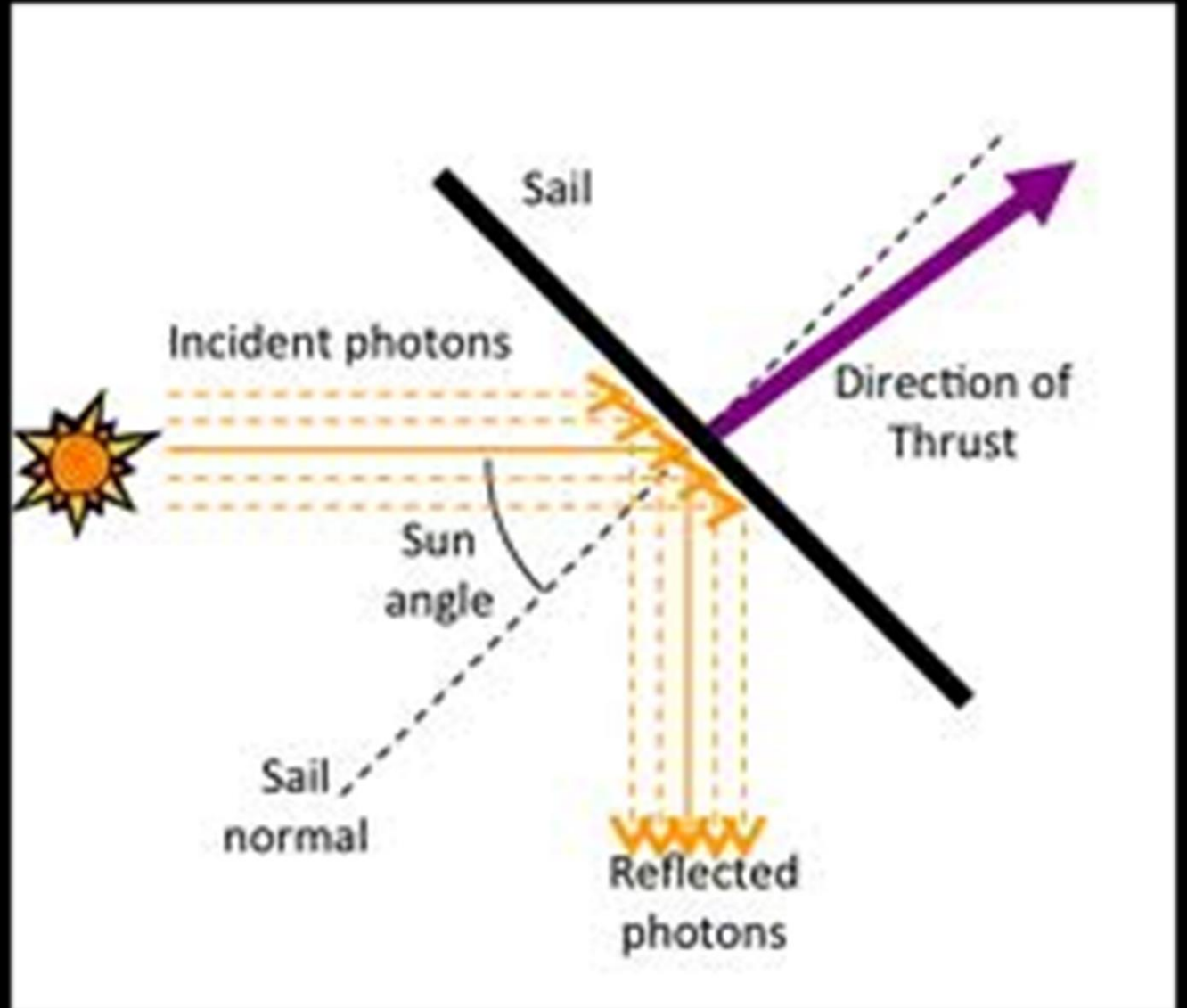
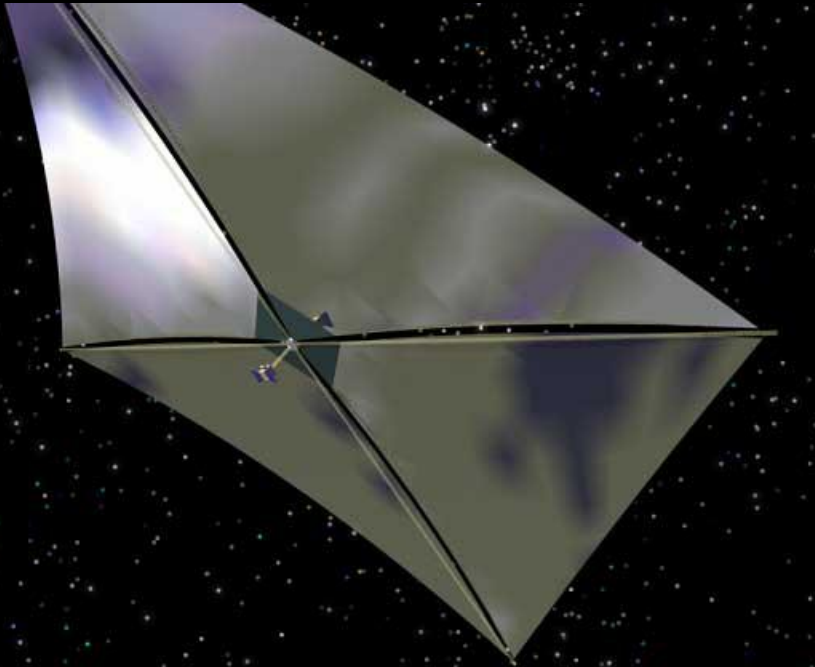
Can we use the environments of space to our advantage?





# Yes we can! With solar sails...

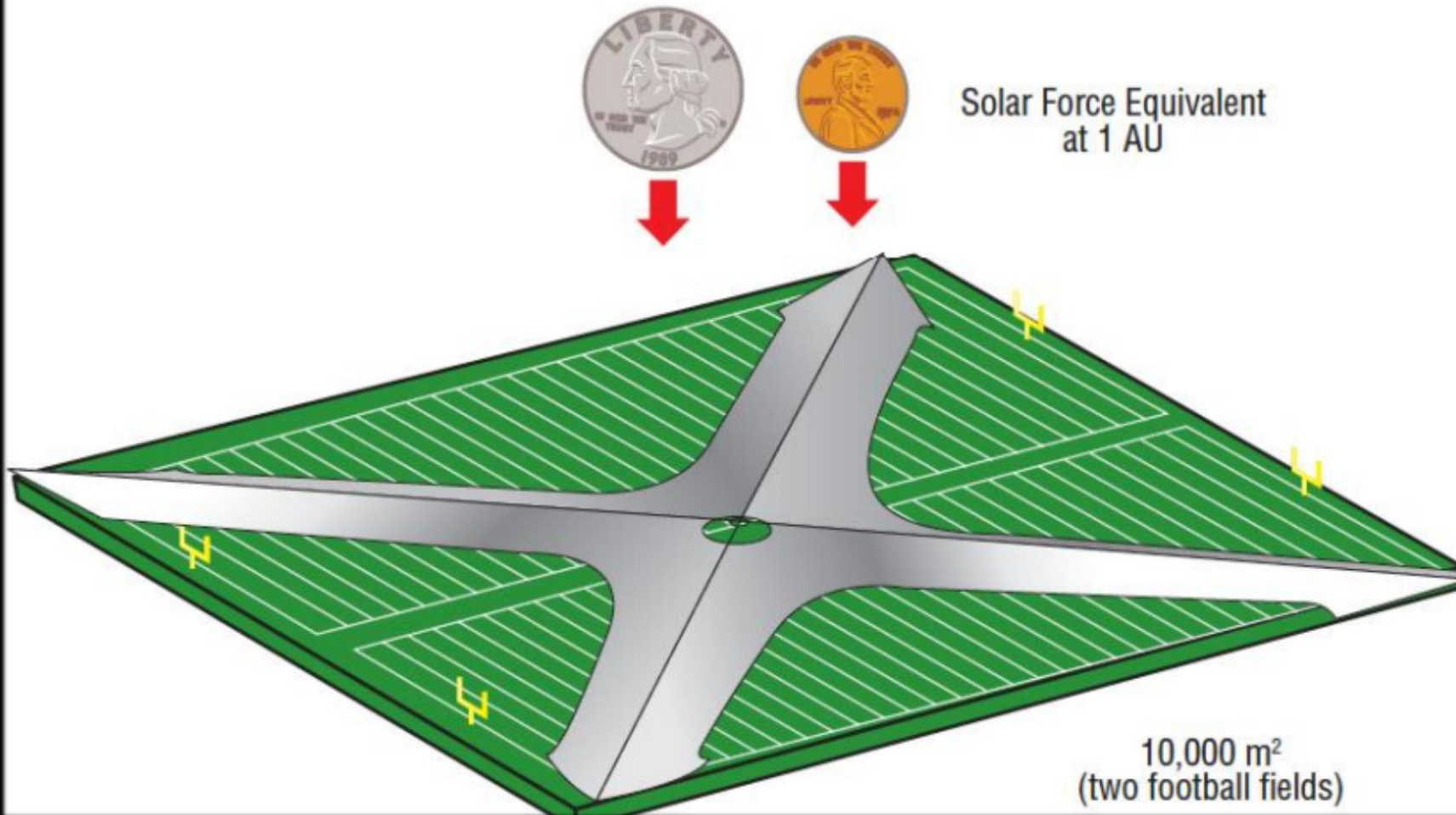
Solar sails use photon "pressure" or force on thin, lightweight, reflective sheets to produce thrust.





# Solar Sails Experience **VERY** Small Forces

- Force on a 100 m x 100 m square sail:







# Solar Sail Propulsion Fundamental Physics

- **Photons carry Momentum**

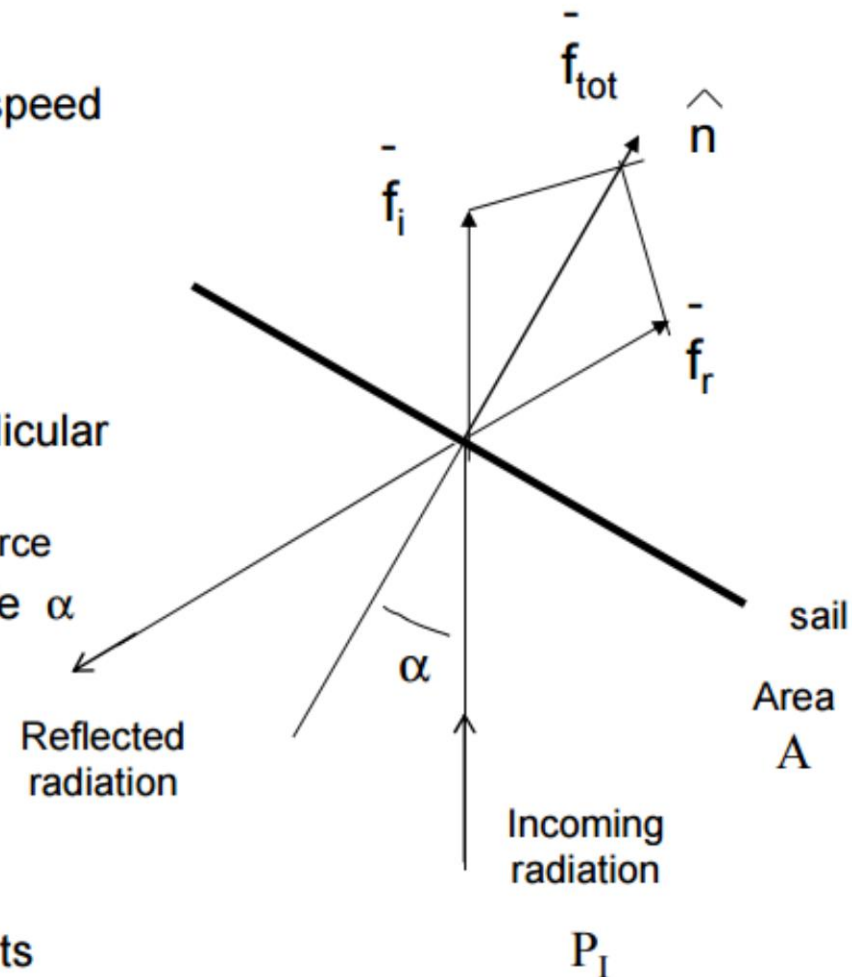
- $p = hv/c$ 
  - $h$  = Planck's,  $v$  = frequency,  $c$  = speed of light

- **Force generated on Reflective Surface**

- Resultant force approximately perpendicular to surface
  - The bigger the surface, the more the force
- Can “steer” sail by changing pitch angle  $\alpha$

- **Small, but potentially Constant Acceleration**

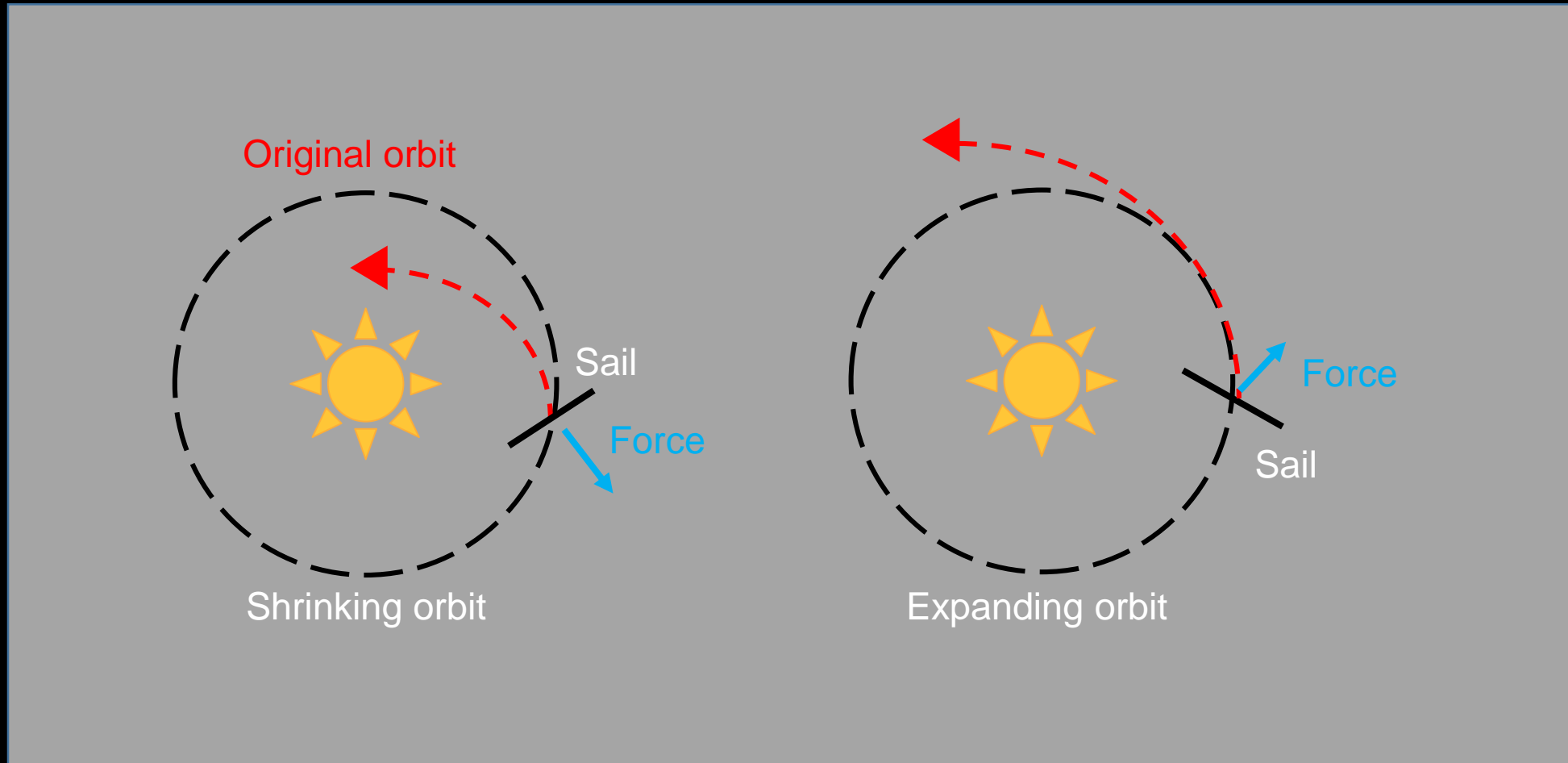
- Potentially unlimited “delta V”
- Allows some otherwise impossible orbits





# Solar Sail Trajectory Control

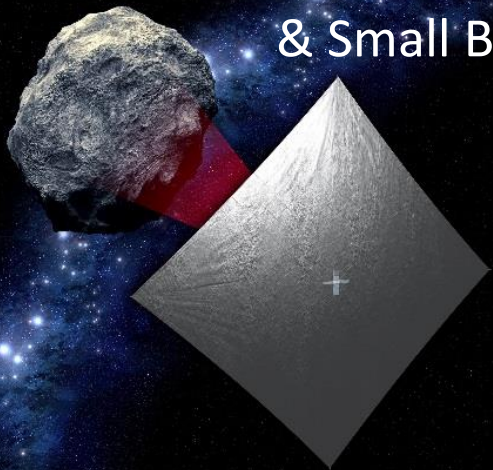
- Solar Radiation Pressure allows inward or outward Spiral



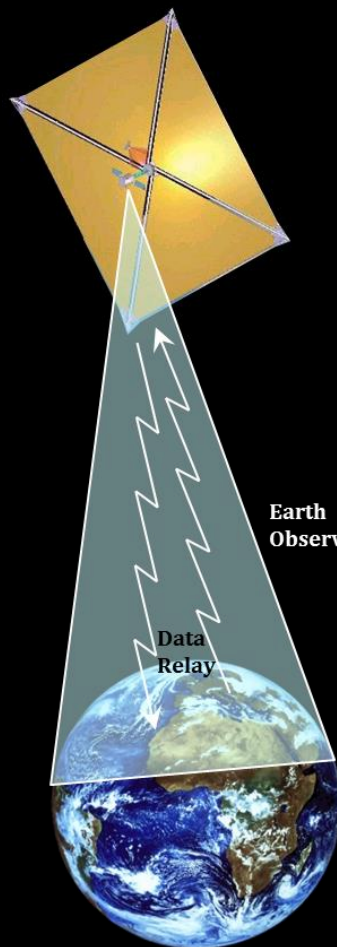


# Potential Solar Sail Applications (A Partial List!)

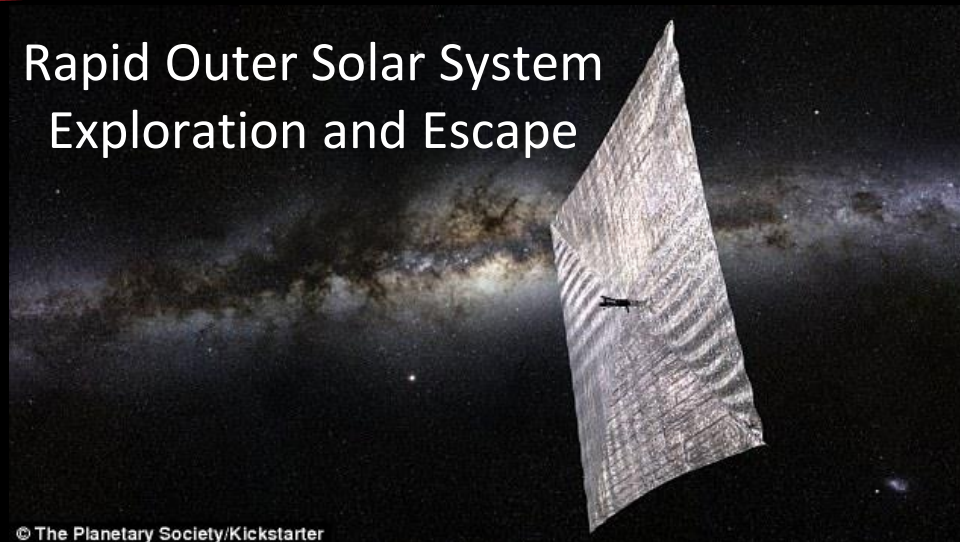
NEA Reconnaissance  
& Small Body Science



Earth Pole Sitting

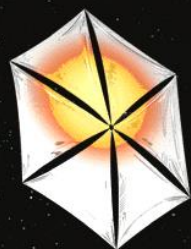


Rapid Outer Solar System  
Exploration and Escape

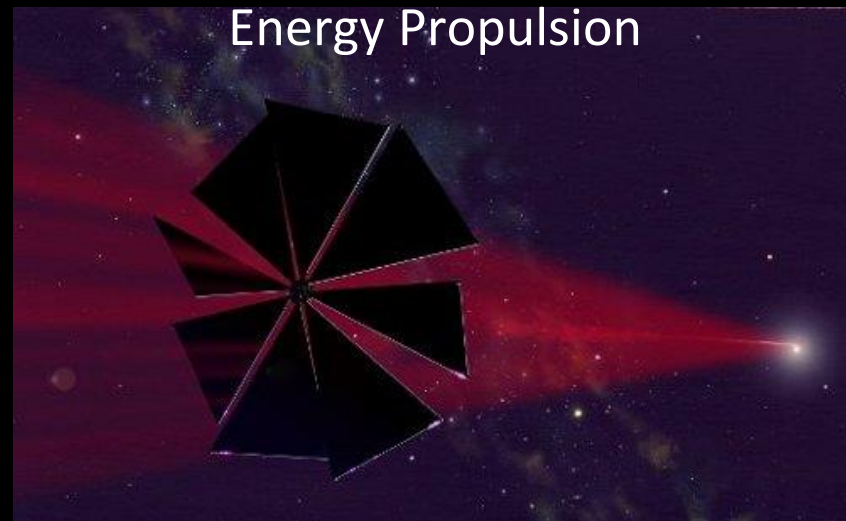


© The Planetary Society/Kickstarter

Heliophysics & Out of  
the Ecliptic Science



Toward Higher Performance Beamed  
Energy Propulsion







# Echo II 1964

## Solar thrust effect on spacecraft orbit



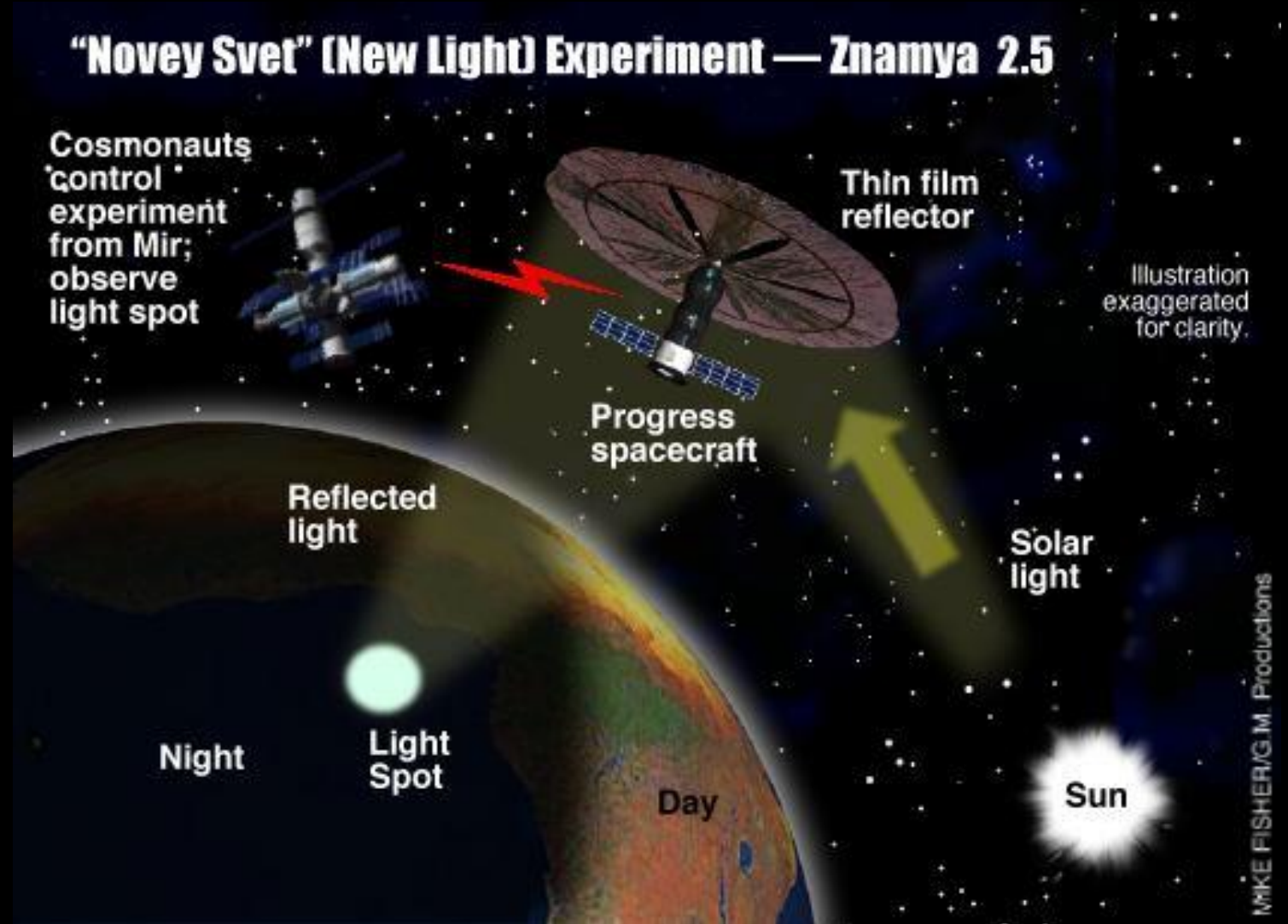
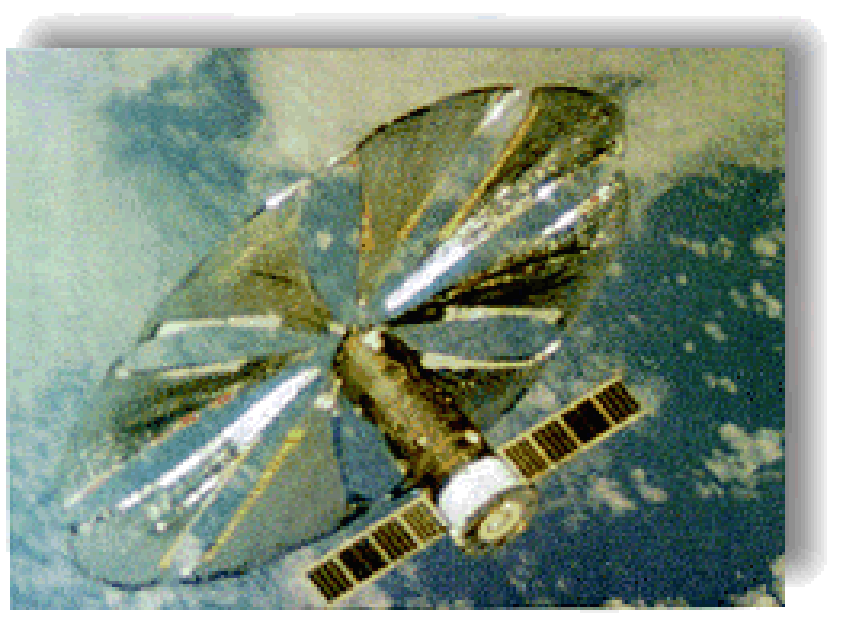
When folded, the satellite was packed into the 41-inch diameter canister shown in the foreground.

- 135-foot rigidized inflatable balloon satellite
- laminated Mylar plastic and aluminum
- placed in near-polar Orbit
- passive communications experiment by NASA on January 25, 1964





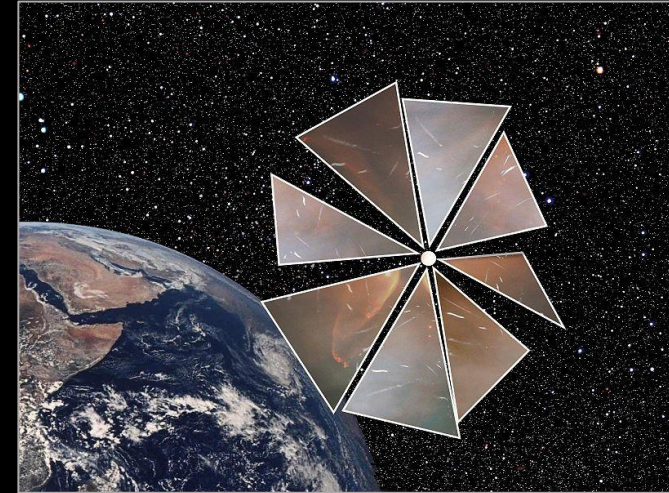
# Znamya (Space Mirror)





# The Planetary Society's Cosmos-1 (2005)

- 100 kg spacecraft
- 8 triangular sail blades deployed from a central hub after launch by the inflating of structural tubes.
  - Sail blades were each 15 m long
  - Total surface area of 600 m<sup>2</sup>
- Launched in 2005 from a Russian Volna Rocket from a Russian Delta III submarine in the Barents Sea.

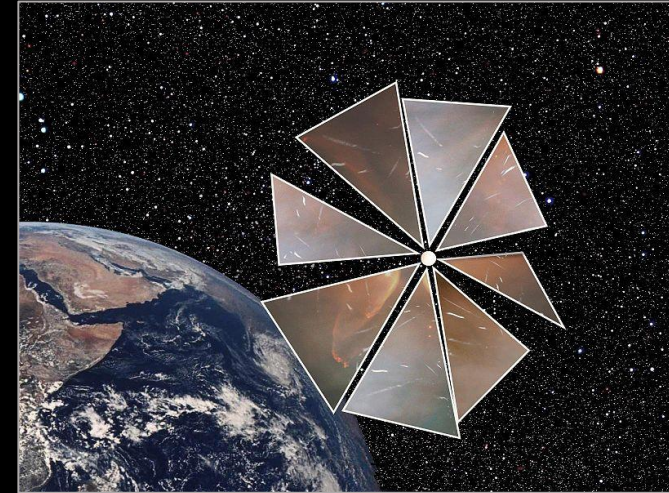






# The Planetary Society's Cosmos-1 (2005)

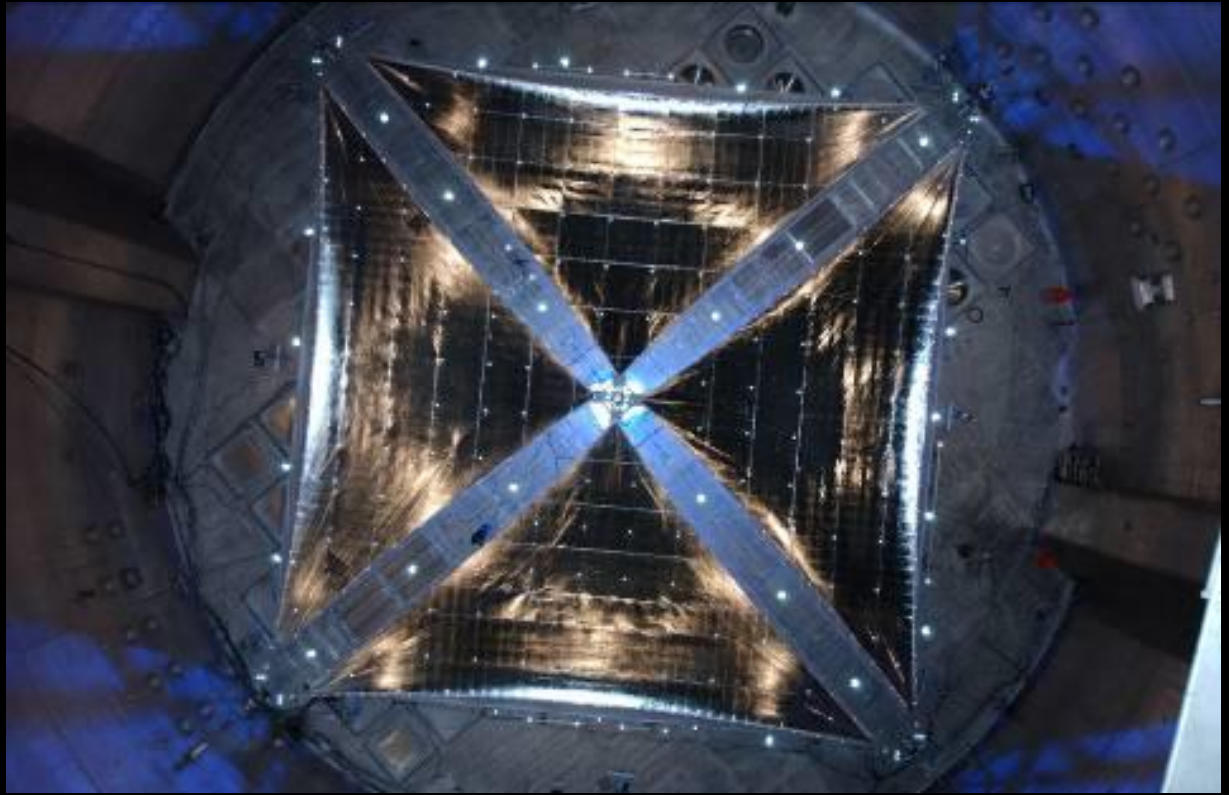
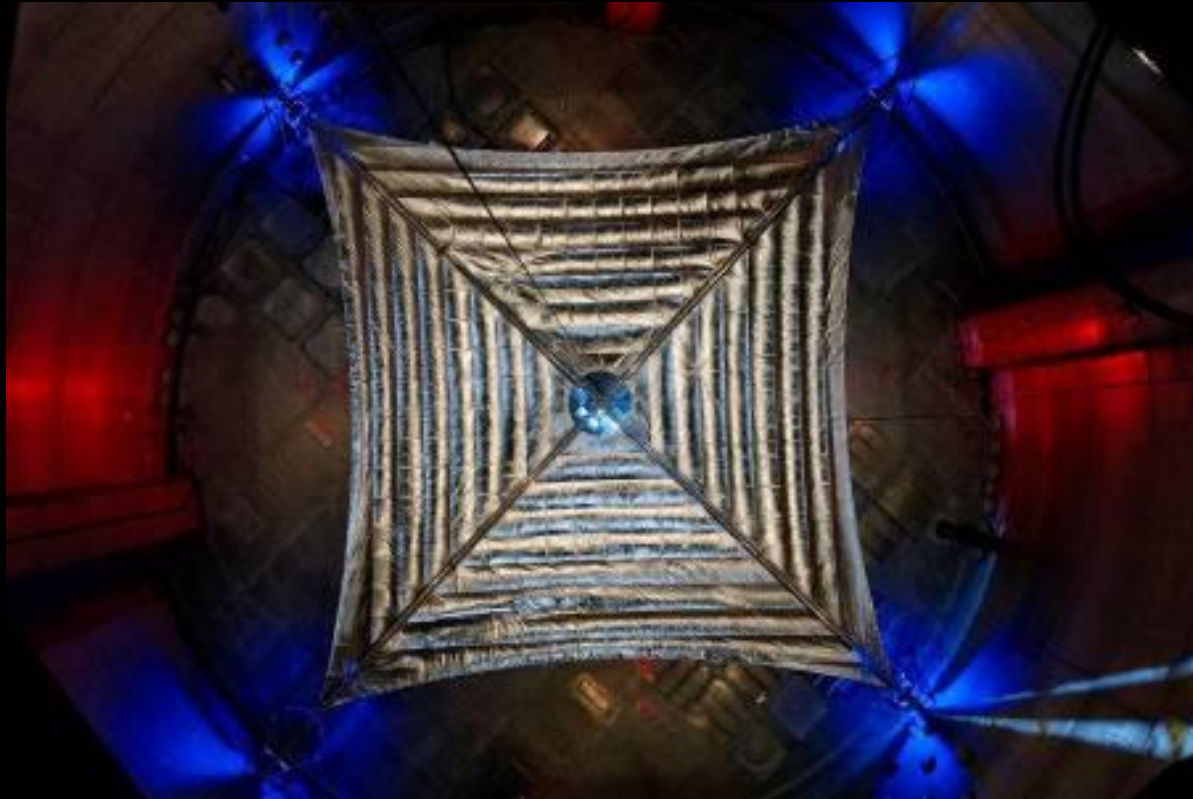
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  - Sail blades were each 15 m long
  - Total surface area of 600 m<sup>2</sup>
- Launched in 2005 from a Russian Volna Rocket from a Russian Delta III submarine in the Barents Sea.



**Rocket Failed.**



# NASA Ground Tested Solar Sails in the Mid-2000's

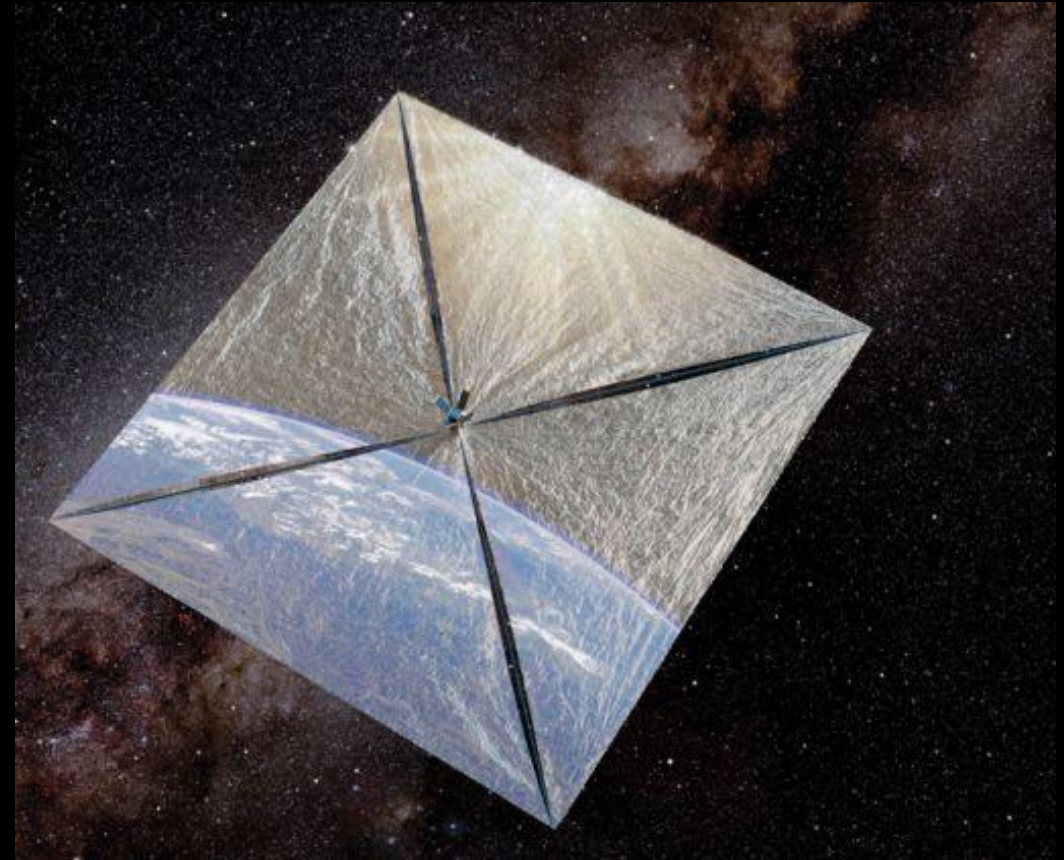






# NASA Space Technology Demo (2009)

- Planned to be a space flight demonstration of the solar sail
- developed and tested as part of the ground sail test program



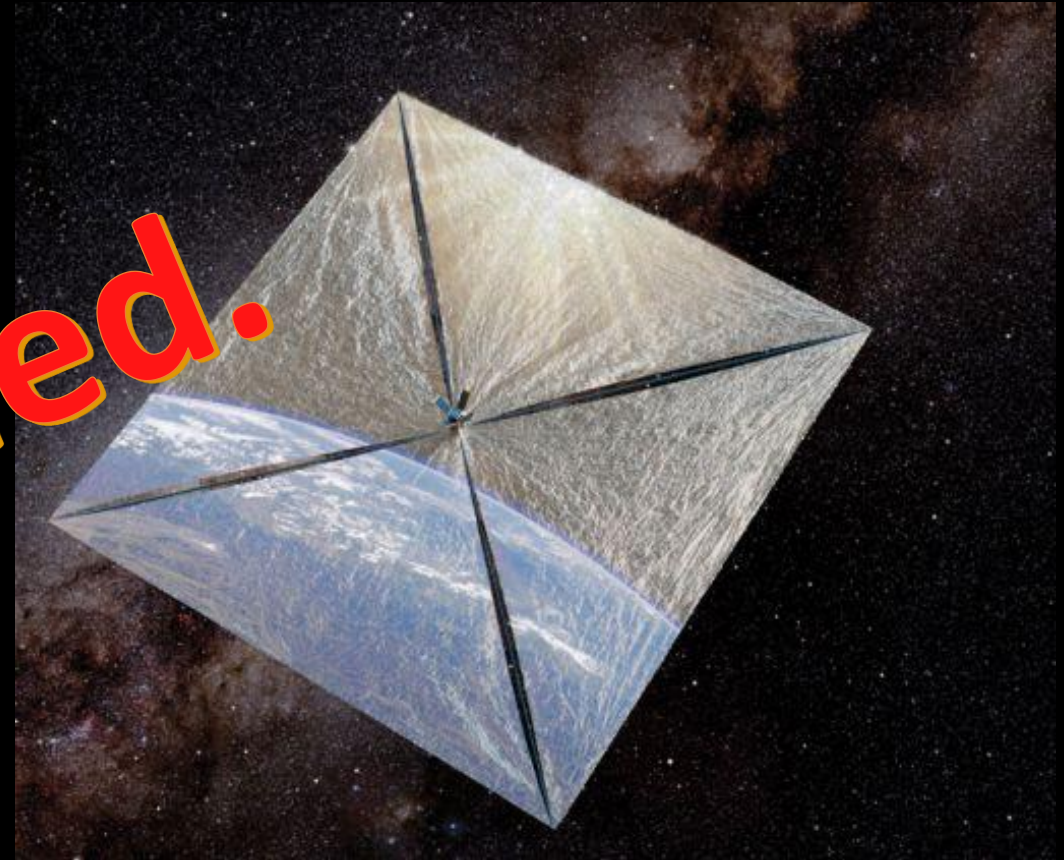




# NASA Space Technology Demo (2009)

- Planned to be a space flight demonstration of the solar sail
- developed and tested as part of the ground sail test program

**Cancelled.**

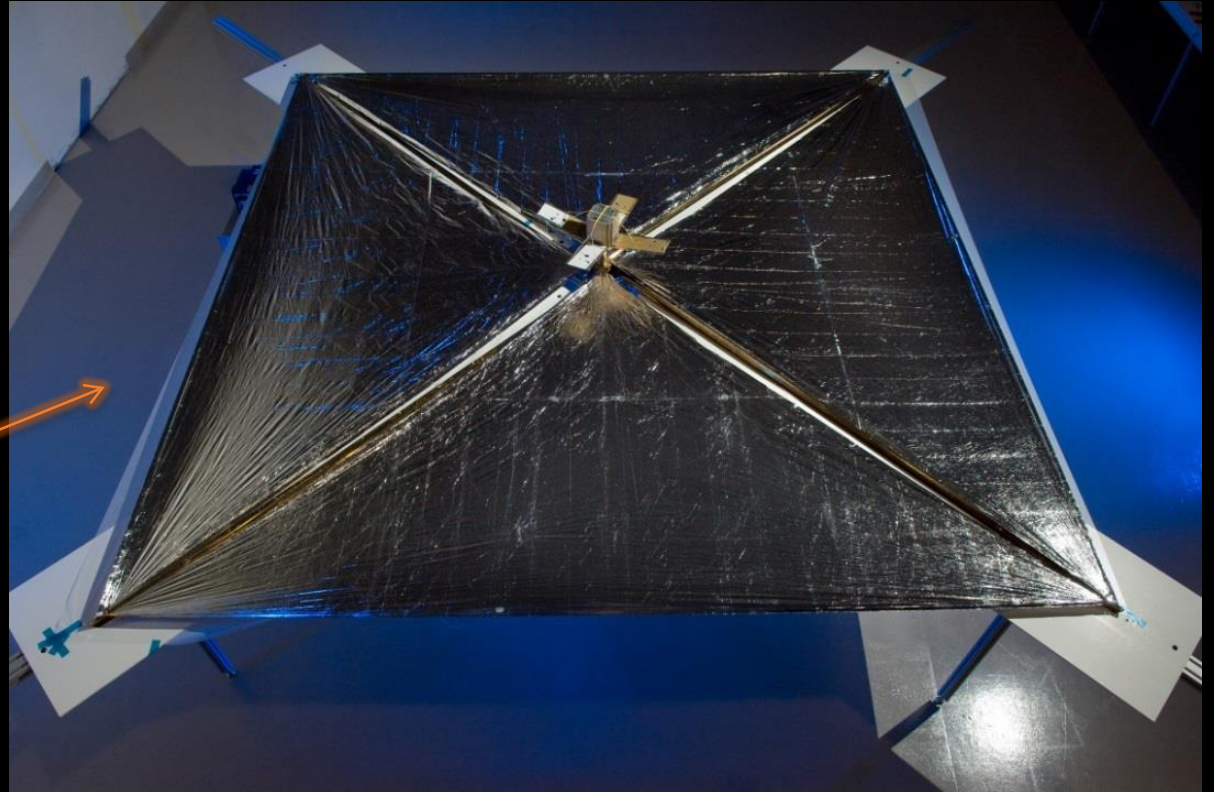
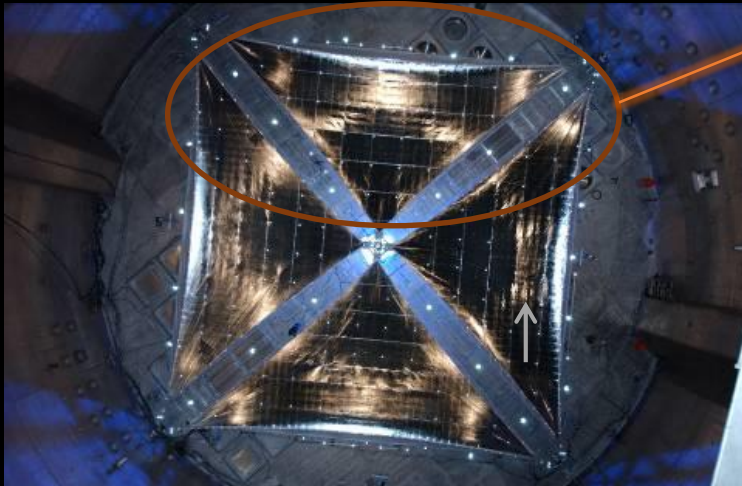




# NanoSail-D Demonstration Solar Sail

## Mission Description:

- 10 m<sup>2</sup> sail
- Made from tested ground demonstrator hardware

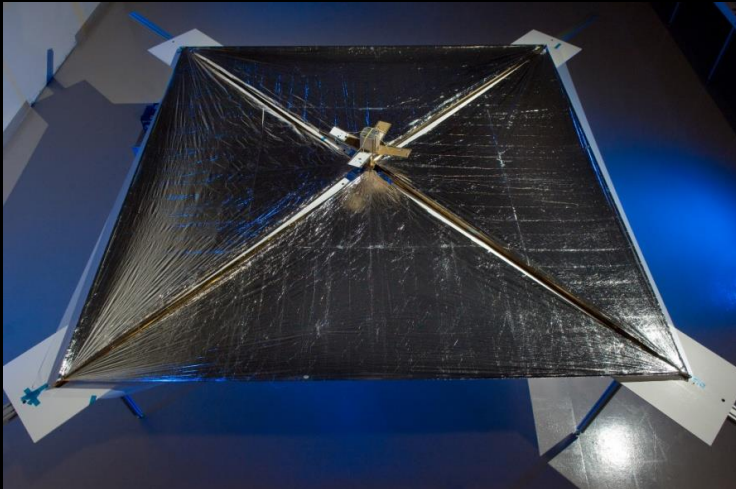




# NanoSail-D1 Flight (2008)

## Launch:

- Falcon-1, flight 3
- Kwajalein, Missile Range
- Primary payload: Air Force PnPSat





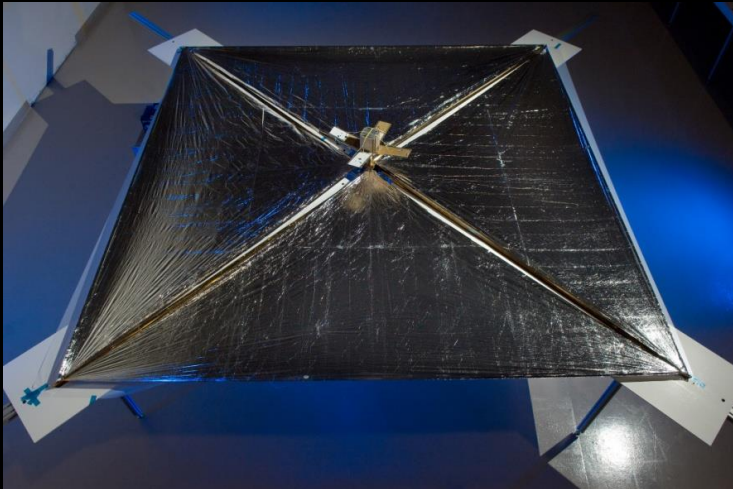


# NanoSail-D1 Flight (2008)

## Launch:

- Falcon-1, flight 3
- Kwajalein, Missile Range
- Primary payload: Air Force PnPSat

**Rocket Failed.**





# NanoSail-D2 Mission Configuration (2010)

## 3U CubeSat: 10 cm X 10 cm X 34 cm

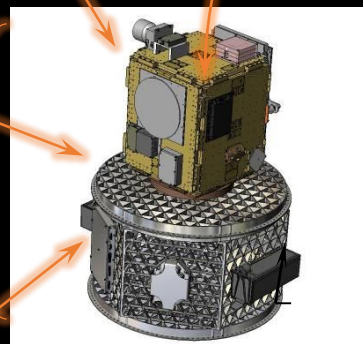
- Deployed CP-1 sail: 10 m<sup>2</sup> Sail Area (3.16 m side length)
- 2.2 m Elgiloy Trac Booms
- UHF and S-Band communications

Nanosail-D2 in Orbit August 19 2011 01h 19m 28s UT  
Clay Center Observatory at Dexter and Southfield Schools  
42.307404N, -71.13722W (WGS84)  
www.claycenter.org Focal length: 12,200mm,  
Aperture = 640mm Ritchey-Chretien  
Contact: Ron Dantowitz (rondantowitz@gmail.com)



HSV-1

Adapter

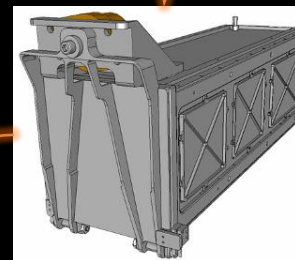


PreSat (ARC)

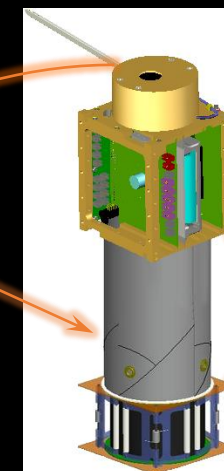
NanoSail-D (MSFC)

Ride Share Adapter  
(Space Access Technology)

Boom & Sail  
Spool  
(ManTech SRS)



PPOD Deployer  
(Cal-Poly)



Spacecraft Bus  
(Ames Research Center)

Bus interfaces  
Actuation  
Electronics  
(MSFC/UAH)

NanoSail-D  
(Aluminum Closeout Panels Not Shown)

Stowed Configuration



NSD-002

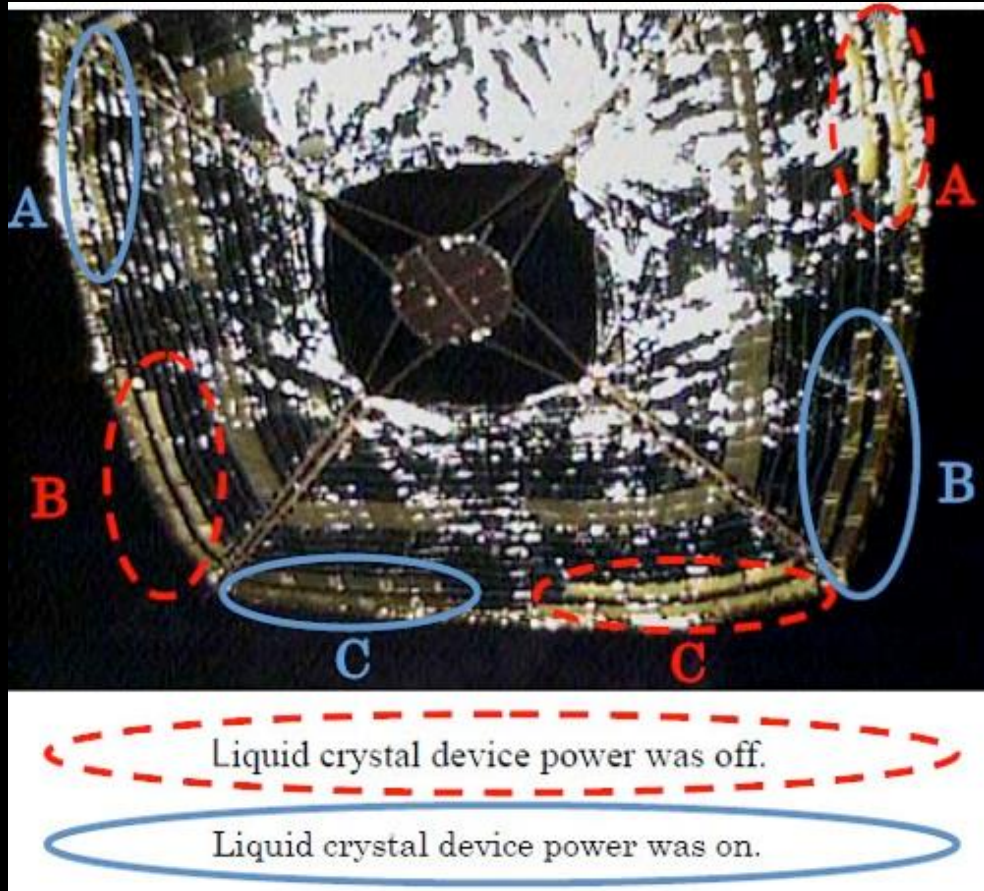
NSD-001



AFRL Satellite (Trailblazer)



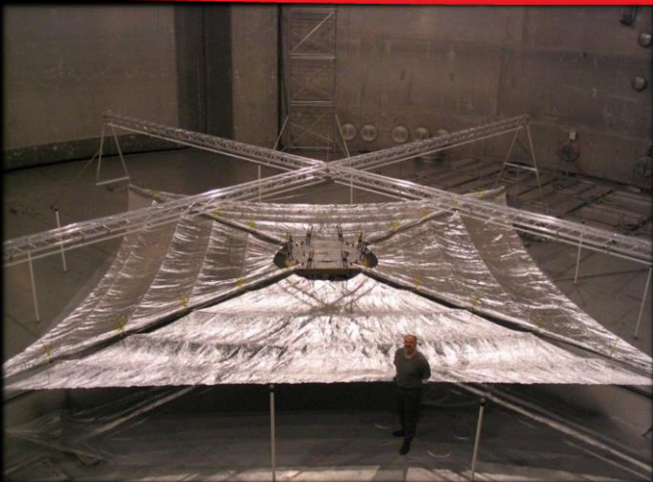
# Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS)







# Sunjammer Solar Sail Demonstration Mission



83 m<sup>2</sup> ISP L'Garde Solar Sail 2004



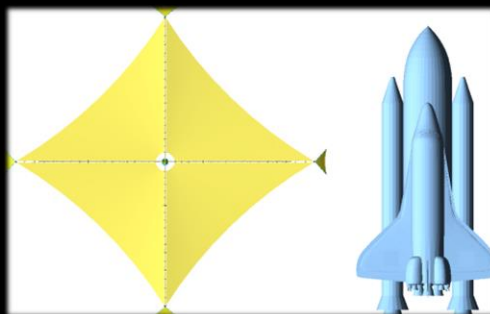
318 m<sup>2</sup> ISP L'Garde Solar Sail 2005

## Design Heritage:

- Cold Rigidization Boom Technology
- Distributed Load Design
- Aluminized Sun Side
- High Emissivity Eclipse Surface
- Beam Tip Vane Control
- Spreader System Design

## Design Features:

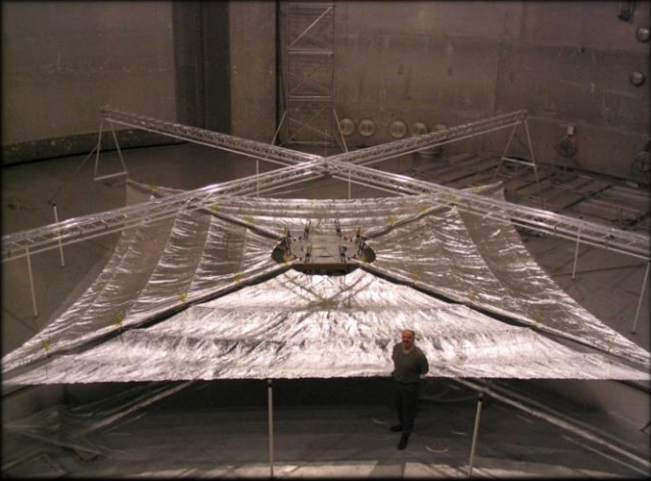
- High density packagability
- Controlled linear deployment
- Structural scalability
- Propellantless operation
- Meets current needs



1200 m<sup>2</sup> L'Garde Sunjammer Launch 2015



# Sunjammer Solar Sail Demonstration Mission



83 m<sup>2</sup> ISP L'Garde Solar Sail  
2004



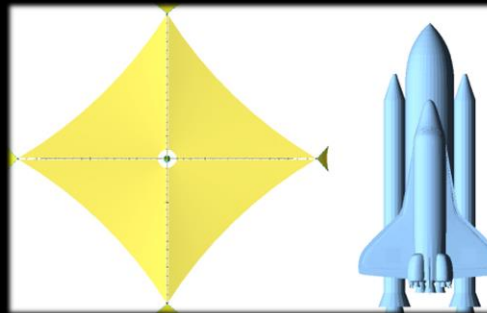
18 m<sup>2</sup> ISP L'Garde Solar Sail  
2005

## Design Heritage:

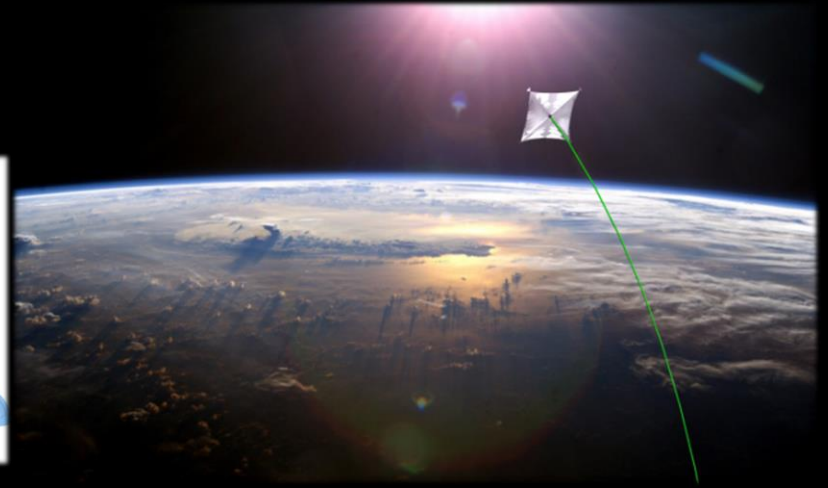
- Cold Rigidization Boom Technology
- Distributed Load Design
- Aluminized Sun Side
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## Design Features:

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1200 m<sup>2</sup> L'Garde Sunjammer Launch  
2015

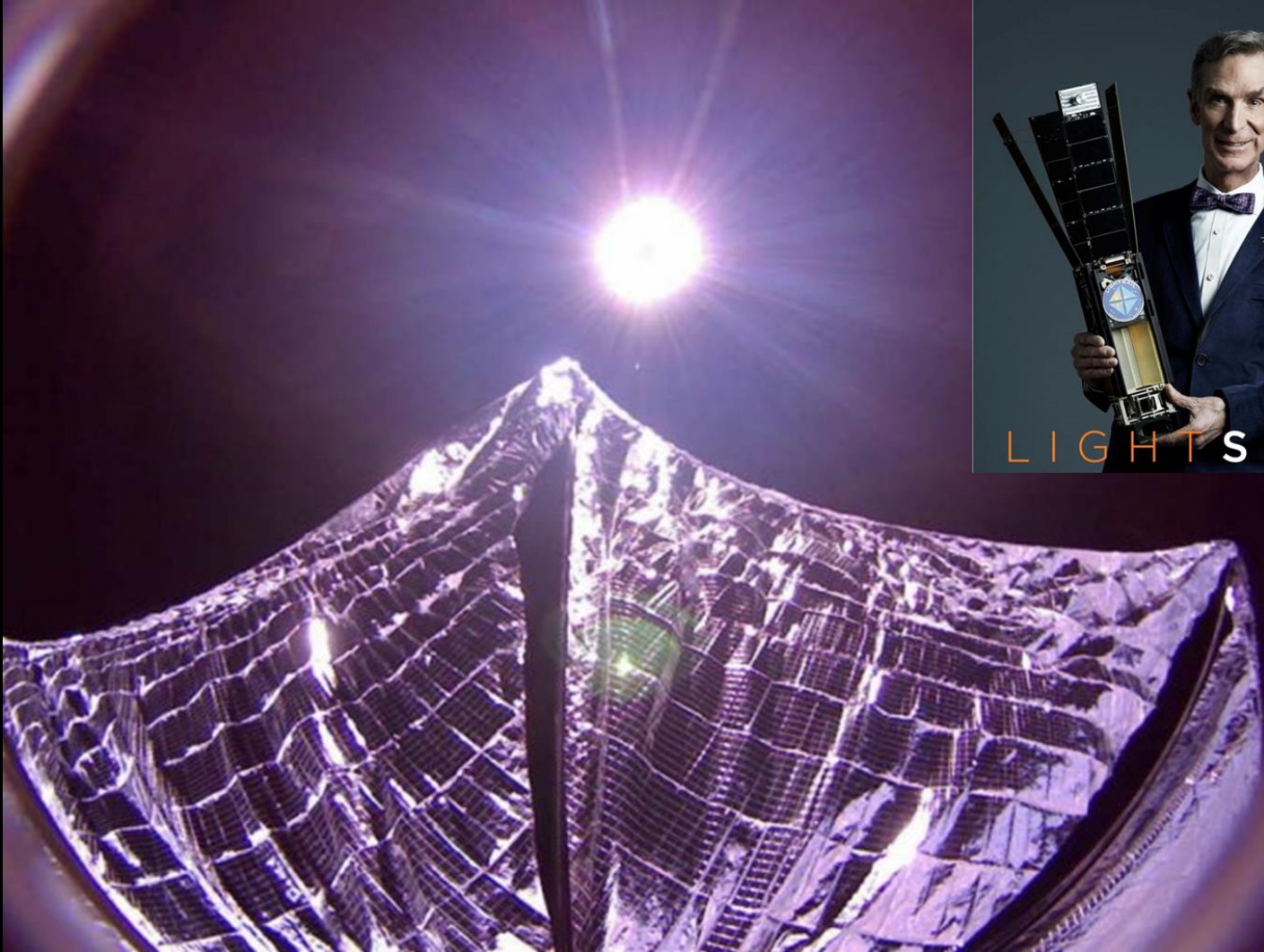






# Lightsail-A

(The Planetary Society)



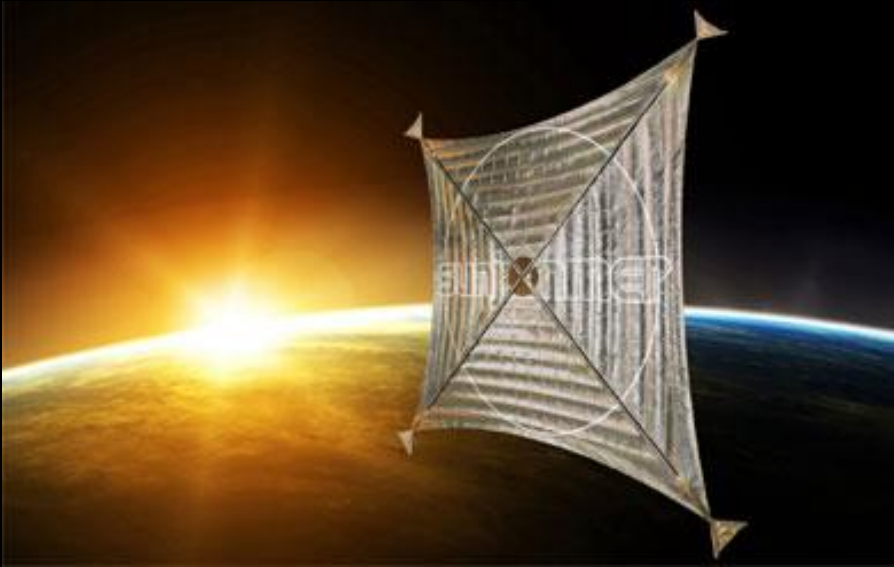
- 32 m<sup>2</sup>
- No active 'sailing'
- 3U CubeSat

**Flew successfully in 2015**

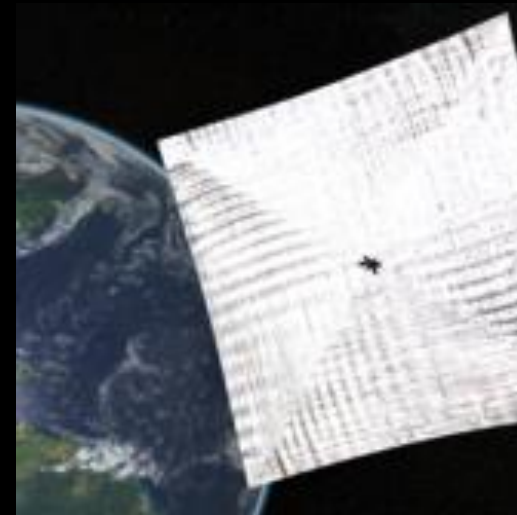
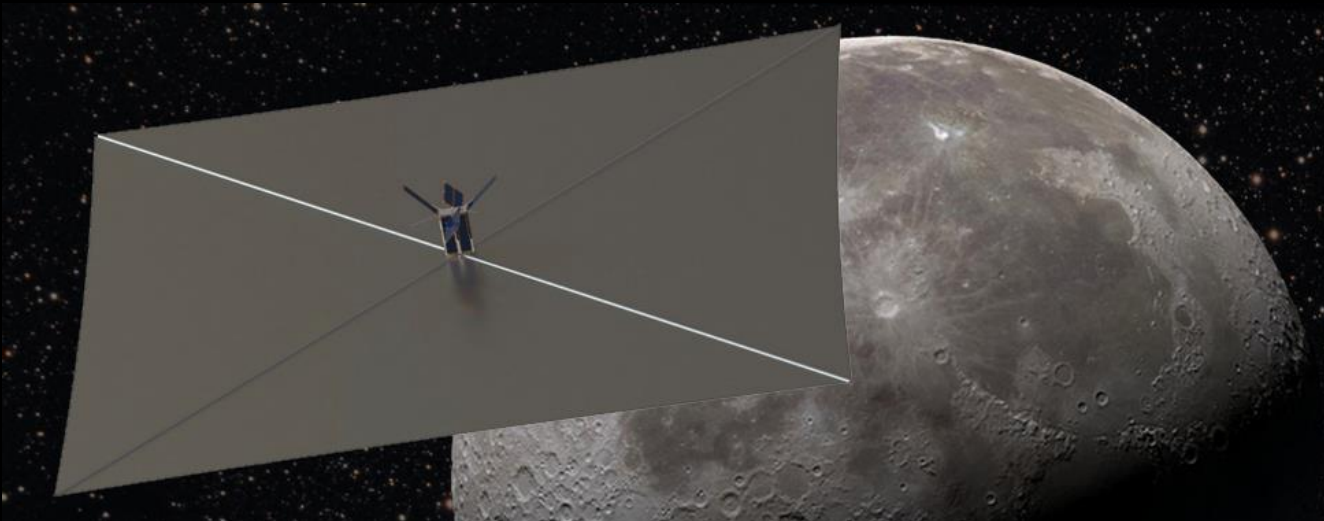




# Solar Sails **TODAY** – Many Missions Planned



- NASA's *NEA Scout*
- The Planetary Society's *LightSail-2*
- The University of Surrey's *InflateSail*
- University of Illinois' *CubeSail*





# NASA's Near Earth Asteroid Scout

## The Near Earth Asteroid Scout Will:

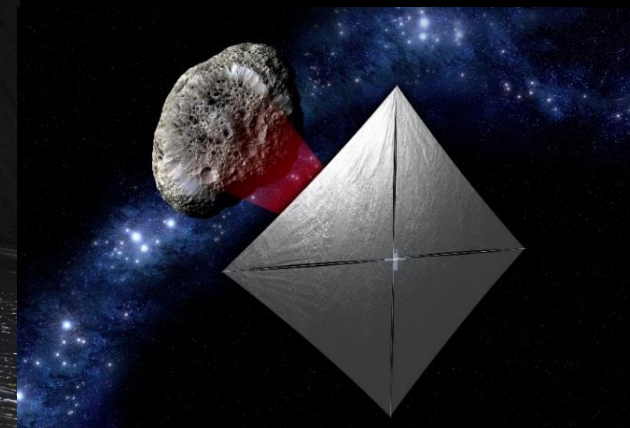
- Image/characterize a NEA during a slow flyby
- Demonstrate a low cost asteroid reconnaissance capability

## Key Spacecraft & Mission Parameters

- 6U cubesat (20 cm X 10 cm X 30 cm)
- ~86 m<sup>2</sup> solar sail propulsion system
- Manifested for launch on the Space Launch System (EM-1/2017)
- Up to 2.5 year mission duration
- 1 AU maximum distance from Earth

## Solar Sail Propulsion System Characteristics

- ~ 7.3 m Trac booms
- 2.5 $\mu$  aluminized CP-1 substrate
- > 90% reflectivity



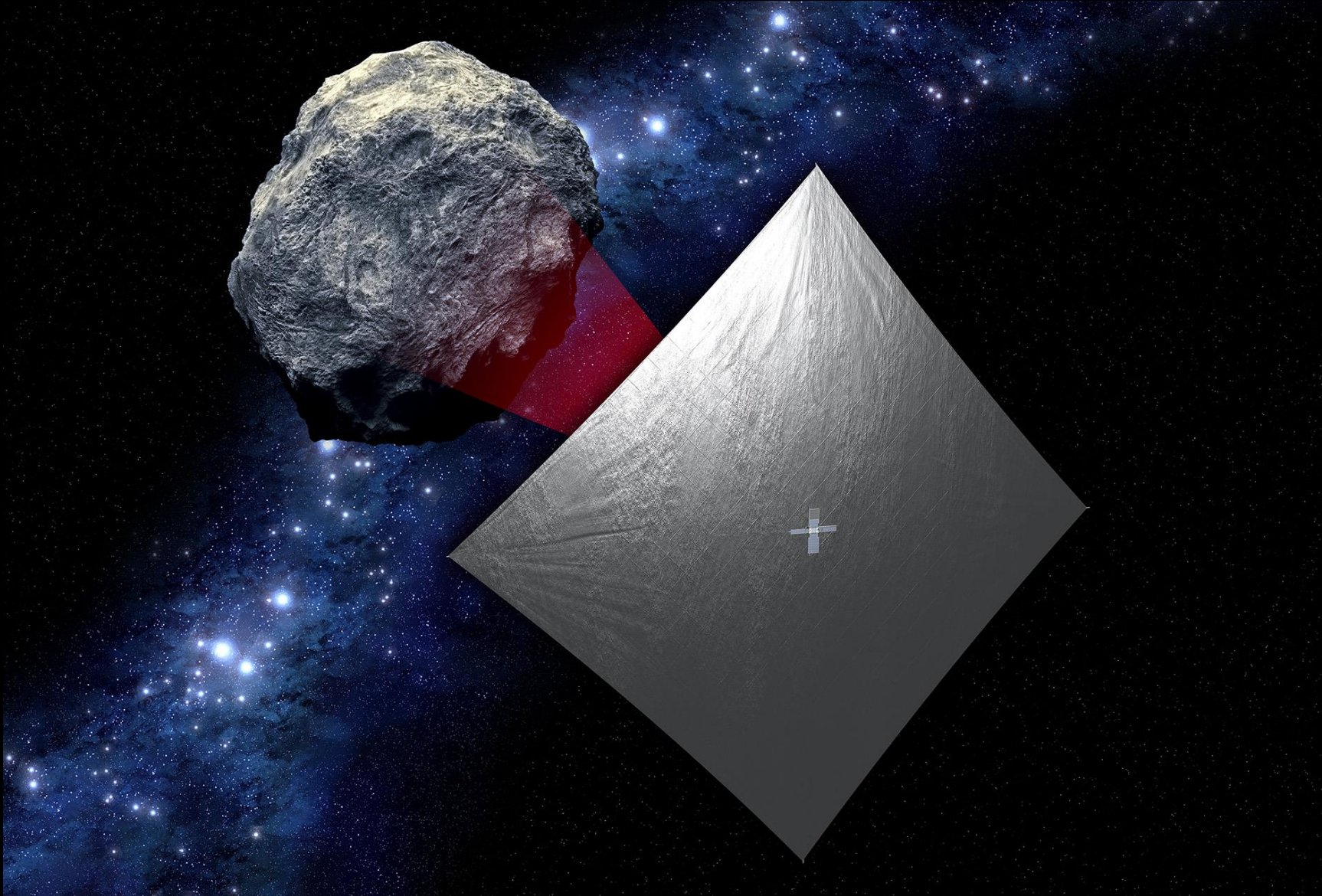


# NEA Scout – Mission Overview





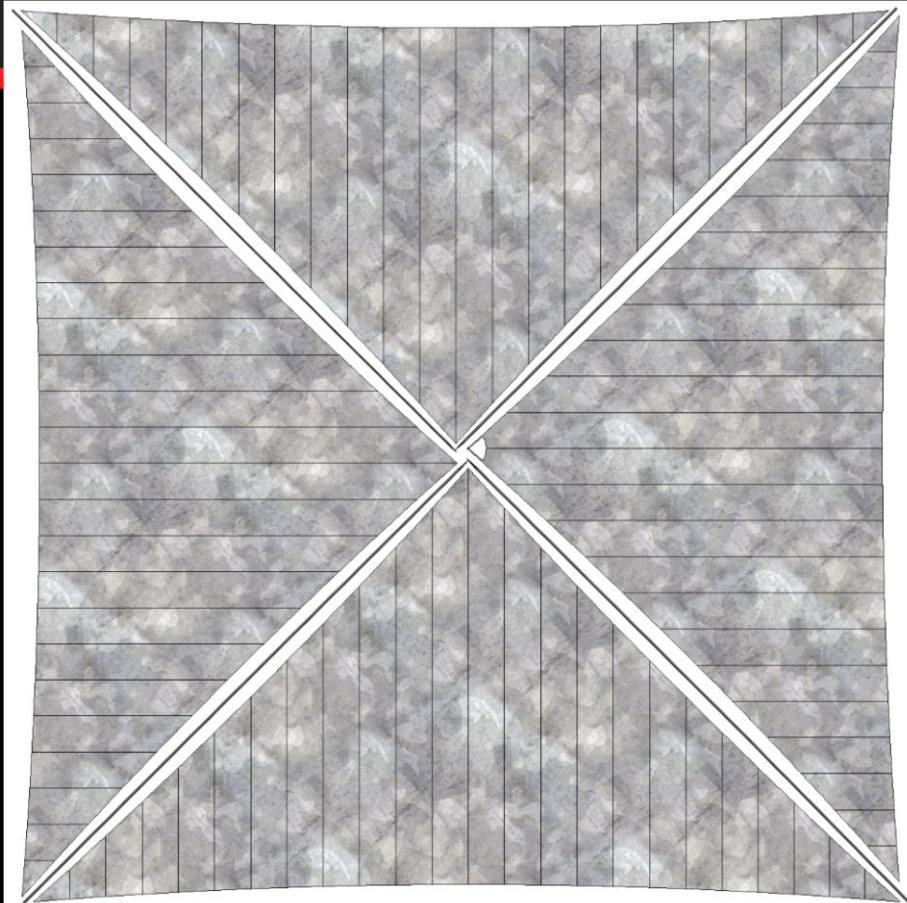
# Near Earth Asteroid (NEA) Scout





# NEA Scout Approximate Scale

Deployed Solar Sail



School Bus



6U Stowed  
Flight System



Folded, spooled and packaged in here

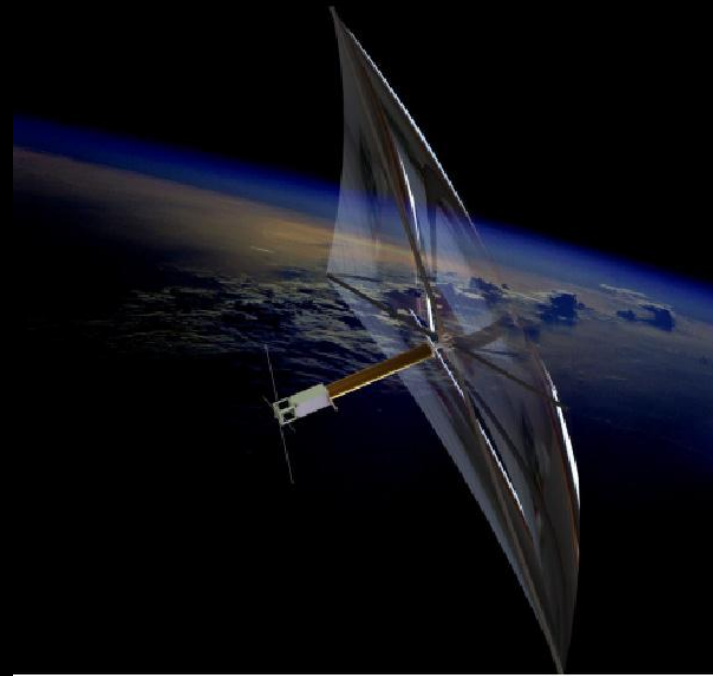




# University of Surrey's InflateSail

**InflateSail** is an inflatable, rigidizable sail for flight in Low Earth Orbit:

- 3U CubeSat with deployed sail area of 10 m<sup>2</sup>
- Sail supported by bistable booms
- Inflation is driven by Cool Gas Generators (CGG): low system mass, long lifespan



*Fig. 1: InflateSail design concept*



*Fig. 2: 80 mg CGG* George C. Marshall Space Flight Center

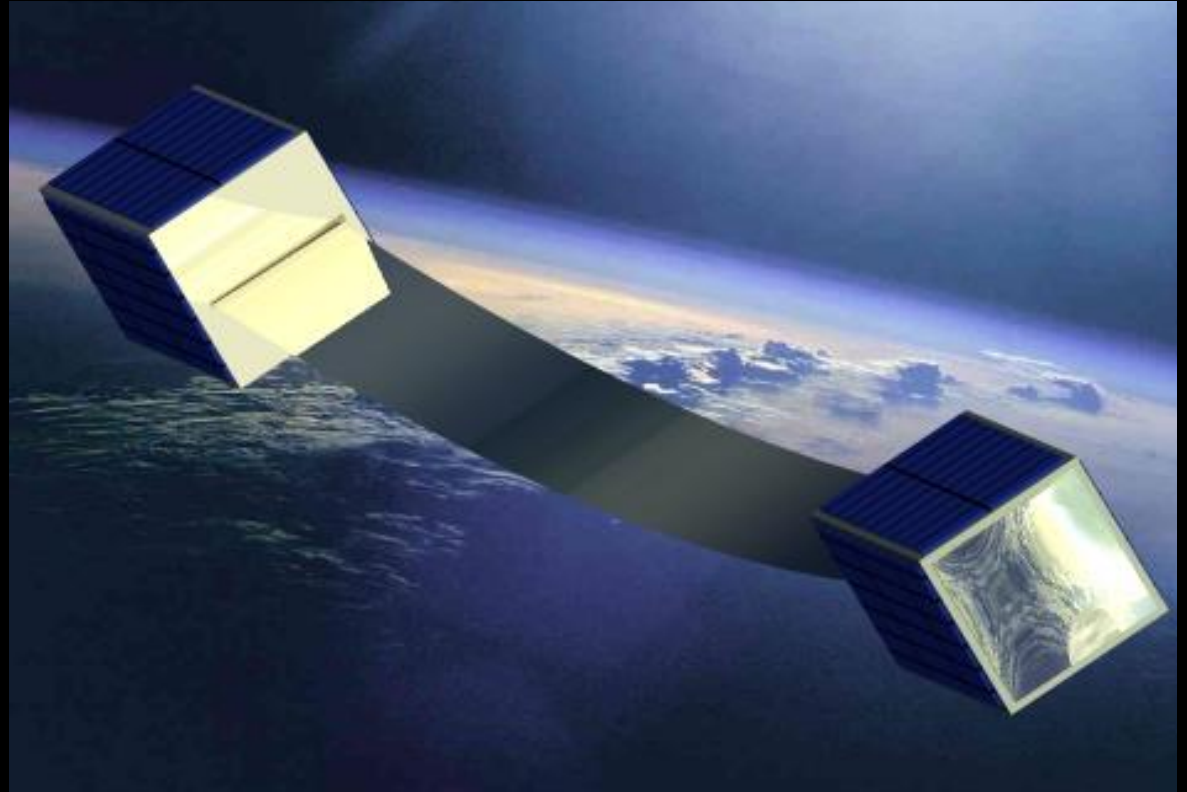






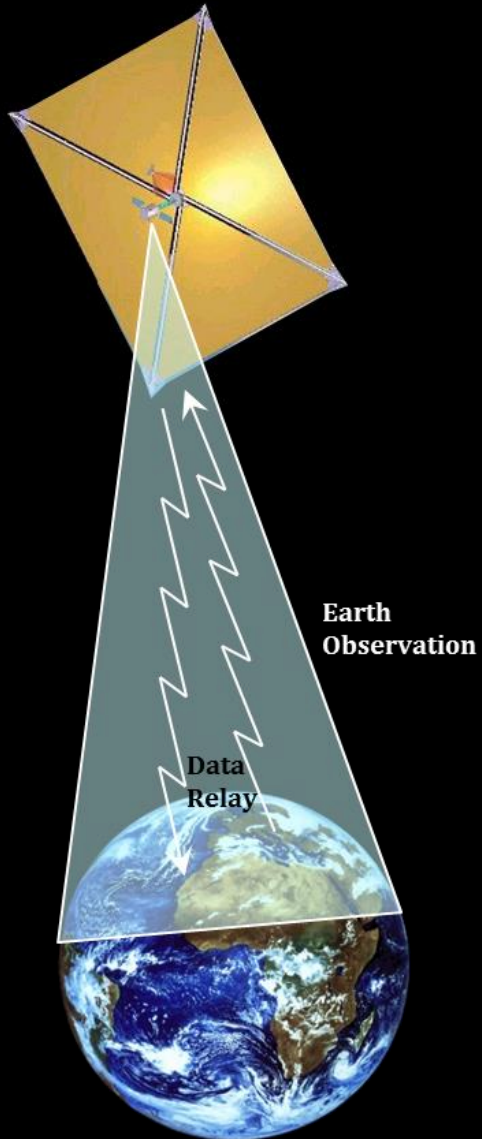
# Cubesail CubeSat Solar Sail Propulsion Demonstration

- The University of Illinois at Urbana-Champaign (UIUC), working with NASA MSFC, NSF, and CU Aerospace, built the flight hardware for a CubeSat-based 20 m<sup>2</sup> solar sail orbit raising demonstration mission
- Selected for flight under the NASA CubeSat Launch Initiative





# Continuous Polar Observations



- Sailcraft over the polar regions of the Earth
- Sail tilted so the light pressure from the sunlight reflecting from it is exactly equal and opposite to the gravity pull of the Earth.





# Interstellar Probe

Deploy a large ( $>10,000 \text{ m}^2$ ) solar sail near the sun to enable travel 5X faster than Voyager

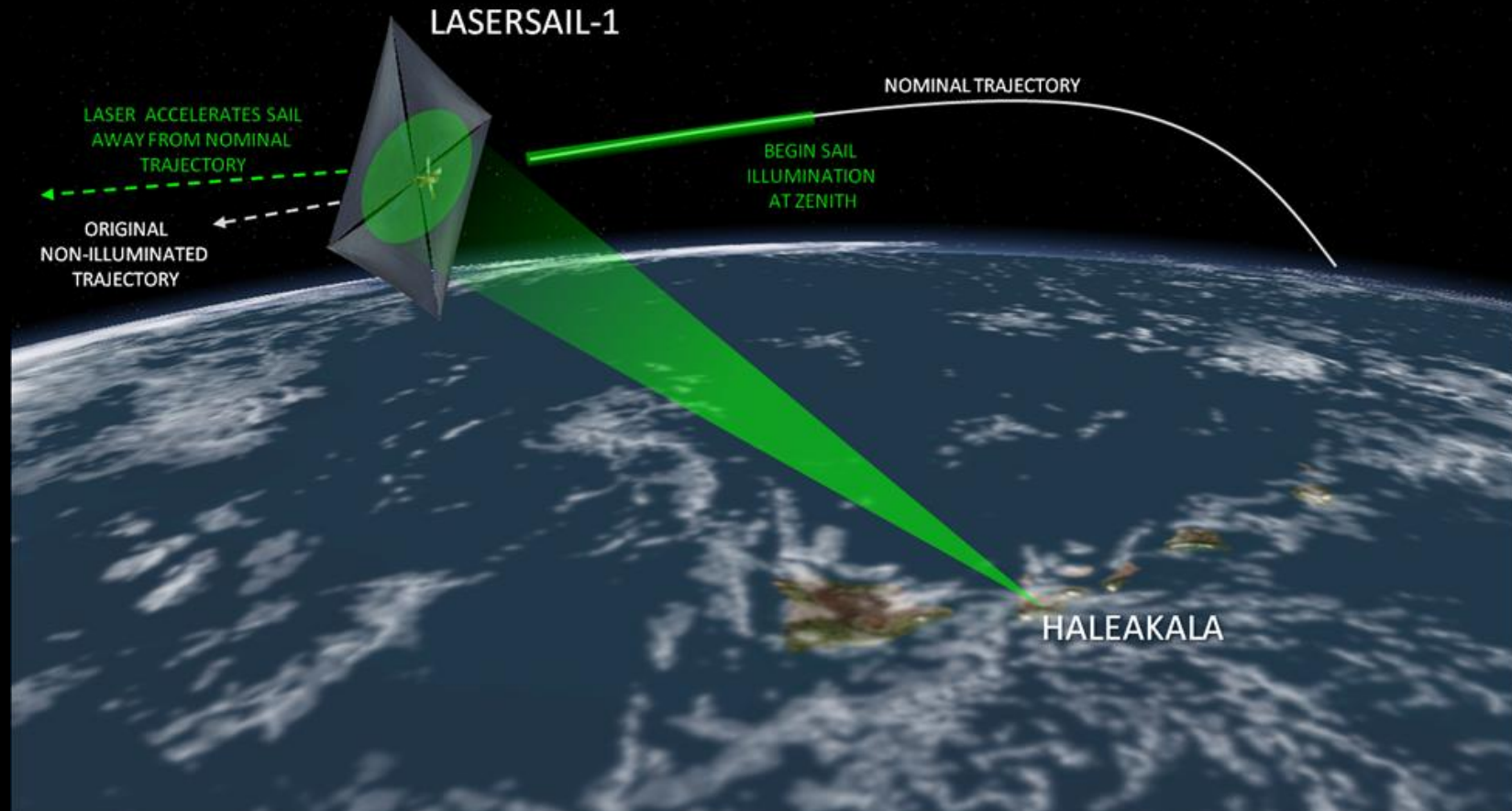


Goal: Reach 250 Astronomical Units within 20 years of launch



# Laser Sailing: The Next Big Step

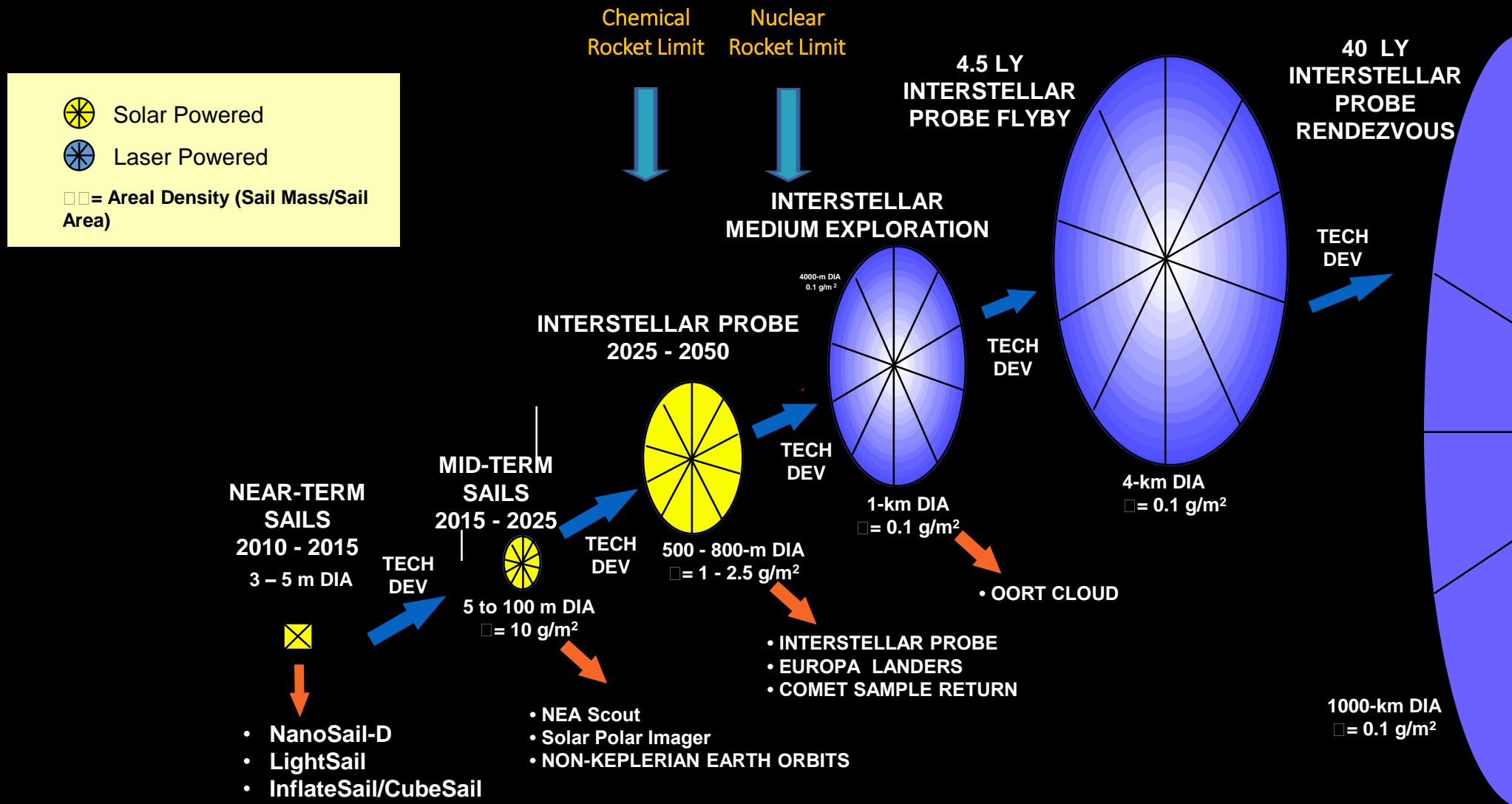
Ground to space laser illumination of a solar sail to impart measurable  $\Delta V$





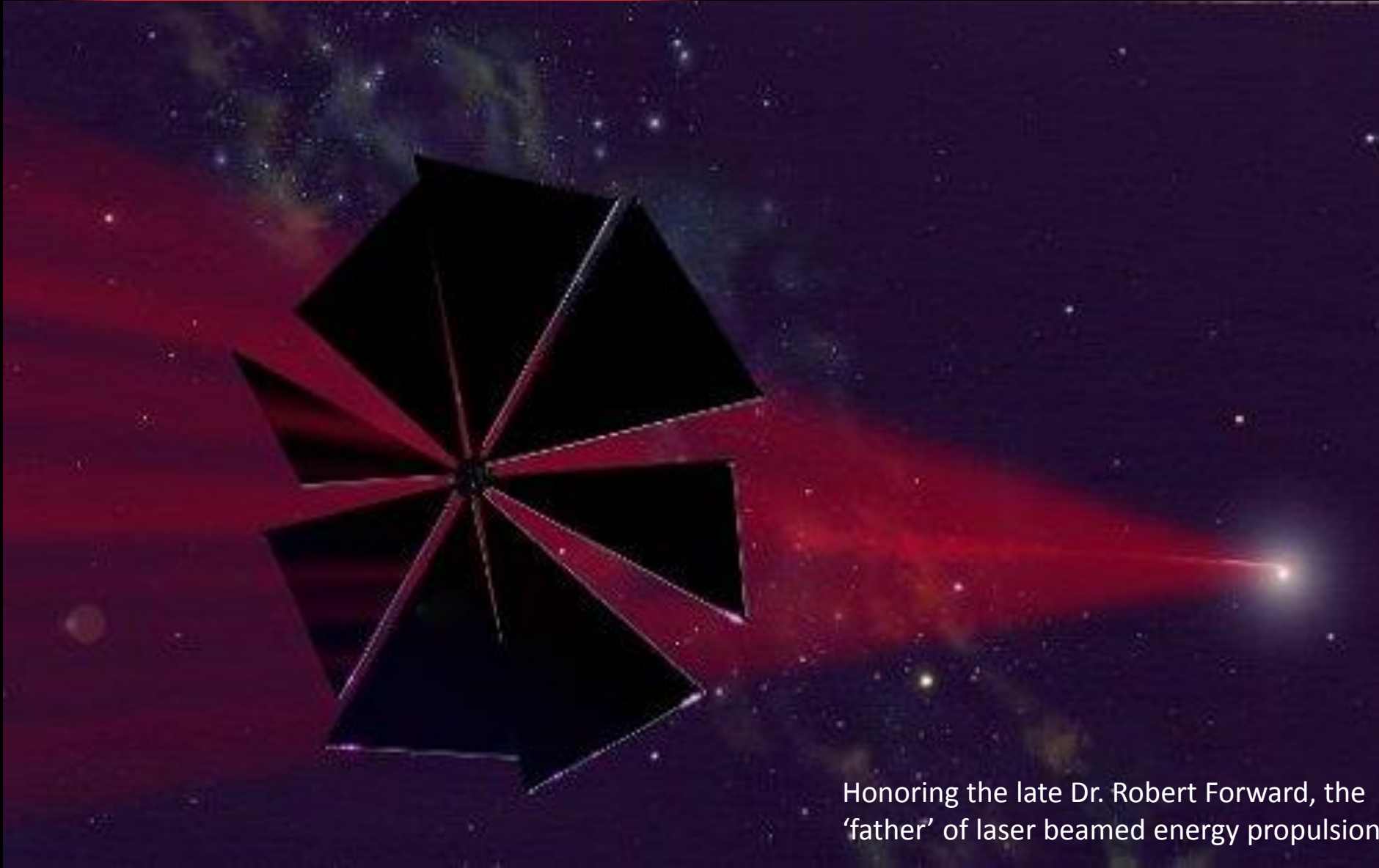


# My Real Motive...





# Solar Sails: A Step Toward the Stars



Honoring the late Dr. Robert Forward, the  
'father' of laser beamed energy propulsion

